Nondistortion Quantum Interrogation using EPR entangled Photons

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We propose a novel scheme for nondistortion quantum interrogation (NQI), defined as an interaction-free measurement which preserves the internal state of the object being detected. In our scheme, two EPR entangled photons are used as the probe and polarization sensitive measurements are performed at the four ports of the Mach-Zehnder interferometer. In comparison with the previous single photon scheme, it is shown that the two photon approach has a higher probability of initial state preserving interrogation of an atom prepared in a quantum superposition. In the case that the presence of the atom is not successfully detected, the experiment can be repeated since the initial state of the atom is unperturbed.

PACS numbers: 03.65.Bz, 42.50.Ct, 03.67.-a

One manifestation of the peculiar wave-particle duality of the light quantum is the possibility of interaction-free measurements, in which the presence of a classical or quantum mechanical object in an interferometer path can be inferred without apparent interaction with the probe photon. This is possible because the presence of an object modifies the interference between different branches of the photon wave function, so that there is a finite probability that the photon will exit the interferometer through a port where it should have not appeared in absence of the object. This is the idea of interaction-free measurement (IFM) first proposed by Elitzur and Vaidman [1]. Later Kwiat *et al.* showed that the efficiency of IFM can be brought arbitrarily close to 1 if one takes advantage of a discrete form of the quantum Zeno effect [2] [3]. More recently, Mitchison and Massar proved that interaction-free discrimination between semi-transparent and complete transparent (absent) objects can also be done with probability approaching unity [4].

It is interesting to ask what effect does the interaction-free measurement have on the object being detected, even though the measurement is "interaction free". As emphasized by Vaidman [5], since the interaction Hamiltonian does not vanish, in general the IFM can change very significantly the quantum state of the observed object. As a matter of fact, if the wave function of the observed object was initially spread out in the space, $|\psi\rangle = |\psi_{spatial}\rangle|\psi_{internal}\rangle$, then a successful IFM necessarily collapses the spatial part of the wave function to the vicinity of the optical path. However, in most cases it is advantageous if we can keep the internal state of the object unperturbed and realize an (internal) initial state preserving IFM, which we may call a nondistortion quantum interrogation (NQI) [6]. For a classical object or two level atom in the ground state, a successful IFM is also a nondistortion interrogation since the internal state of the object is not affected if the probe photon is not absorbed. However, as discussed in a recent paper by Potting *et al.* [7], this problem is more subtle for a quantum mechanical object characterized by its quantum superposition. Using a "which path" argument they showed that the absence of energy exchange during the measurement is not a sufficient condition to preserve the initial state of the object, since the quantum superposition of the object is subject to measurement dependent decoherence. Although it is possible in general to design interaction-free measurement schemes that do preserve the initial state of the quantum object, the scheme they discussed has a very low success probability.

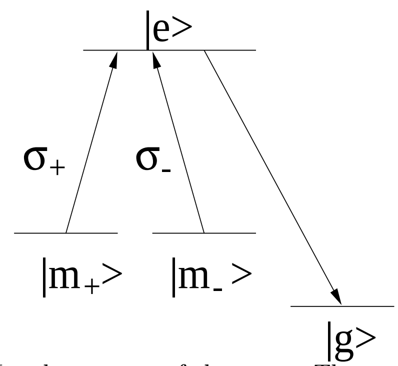

FIG. 1. Level structure of the atom. The atom can make a transition to the excited state $|e\rangle$ from $|m_+\rangle$ or $|m_-\rangle$ by absorbing a circular polarized photon. It then decays rapidly to the stable ground state $|g\rangle$.

The purpose of this paper is to propose a new scheme for NQI, which uses a pair of probe photons. Consider a multilevel atomic system shown in Fig. 1, which is the same model as used in [7]. Starting from the initial degenerate metastable states $|m_+\rangle$ and $|m_-\rangle$, the atom can make a transition to the excited state $|e\rangle$ by absorbing a $+$ or $-$ (circular) polarized photon with unit efficiency. It then decays irreversibly to the ground state $|g\rangle$ very rapidly. The absorption process is therefore

$$\hat{a}^\dagger_\pm|0\rangle|m_\pm\rangle \longrightarrow |S\rangle|g\rangle \qquad (1)$$

where $|S\rangle$ is a scattered photon which we assume will not be reabsorbed by the atom and can be filtered away from the detectors. To investigate the effect of IFM on the initial state of the atom, let us assume that the atom is initially in the superposition

$$|\psi_{atom}\rangle = \alpha|m_+\rangle + \beta|m_-\rangle \qquad (2)$$

where α and β are unknown non-vanishing coefficients satisfying $|\alpha|^2 + |\beta|^2 = 1$.

As illustrated in Fig. 2, the Mach-Zehnder interferometer consists of two identical non-polarizing $50-50$ beam splitters. Note that the interferometer has four ports. We use two photons, one entering from the left lower port and the other from the right lower port, as our probe. Four polarization sensitive photon detectors, $D_{\leftarrow,u}, D_{\leftarrow,l}, D_{\rightarrow,u}, D_{\rightarrow,l}$, are placed at the four ports of the interferometer. When no atom is in the interferometer, the two photons exit with certainty from the two upper ports (therefore $D_{\leftarrow,u}$ and $D_{\rightarrow,u}$ fire). In presence of the atom, the interference is modified so that one or both photons have a chance to exit from the lower ports. So in the case that no absorption happened, any of the following combinations indicates the presence of the atom in the interferometer (hence a successful IFM): $D_{\leftarrow,u}$ and $D_{\rightarrow,l}$ fire; $D_{\leftarrow,l}$ and $D_{\rightarrow,u}$ fire; $D_{\leftarrow,l}$ and $D_{\rightarrow,l}$ fire. These are not necessarily nondistortion interrogation though. We will show, by properly choosing the polarization of the probe photons and photon detectors, we can perform a nondistortion interrogation of the atom with success probability half that in the original EV scheme for a two level atom [1].

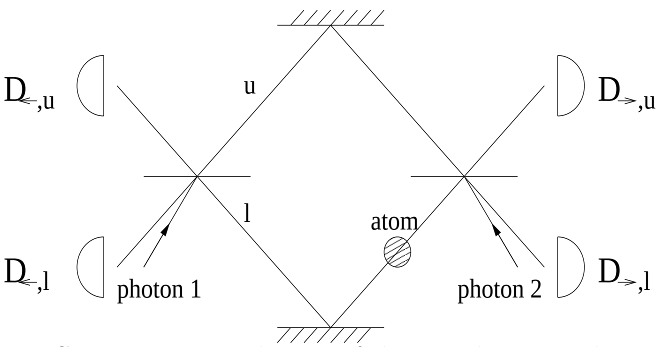

FIG. 2. Experimental setup of the two-photon nondistortion quantum interrogation. The two probe photons enter the Mach-Zehnder interferometer from left and right lower port respectively. Polarization sensitive measurements of the photons are performed at the four ports of the interferometer.

At first glance, it appears that the two photon approach is the same with doing the measurement twice with the single photon scheme as in [7], once with a left entering photon and once with a right entering one. This is not true for two reasons. First, we can have correlations between the two probe photons. Second, in the two photon scheme the states of the two photons are measured together at the end of the experiment and the wave function of the whole system (atom plus photons) is collapsed only once. To make it clearer let us first look at the case that two independent photons are used as the probe. Take the state of the two photons to be

$$|\psi_{photon}\rangle = \hat{a}^{\dagger}_{\rightarrow,l,+}\hat{a}^{\dagger}_{\leftarrow,l,-}|0\rangle \tag{3}$$

Note three indices are used to specify the state of a photon: the propagation direction ($\rightarrow$ or $\leftarrow$); the optical path it follows ($l$ower or $u$pper); and the direction of polarization ($+$ or $-$). The effect of the beam splitters on the photons is as follows:

$$\begin{aligned} \hat{a}^{\dagger}_{\rightleftarrows,l}|0\rangle &\longrightarrow \frac{1}{\sqrt{2}}(\hat{a}^{\dagger}_{\rightleftarrows,u} \pm i\hat{a}^{\dagger}_{\rightleftarrows,l})|0\rangle \\ \hat{a}^{\dagger}_{\rightleftarrows,u}|0\rangle &\longrightarrow \frac{1}{\sqrt{2}}(\hat{a}^{\dagger}_{\rightleftarrows,l} \pm i\hat{a}^{\dagger}_{\rightleftarrows,u})|0\rangle \end{aligned} \tag{4}$$

each time the photon is reflected its wave function picks up a phase shift of $\pm\pi/2$ depending on the propagation direction of the photon.

Suppose that the possible location of the atom is in the lower arm of the interferometer, then only photons following the lower path interact with the atom. In addition, assume that the decaying from the excited state to the ground state is so rapid that we do not need to consider the stimulated emission of the atom when it is in the excited state. Then the initial state $|\psi_{photon}\rangle|\psi_{atom}\rangle$ evolves into the following final state:

$$\begin{aligned} |\psi_{final}\rangle = &+\frac{1}{2}\hat{a}^{\dagger}_{\rightarrow,u,+}\hat{a}^{\dagger}_{\leftarrow,u,-}|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\ &-\frac{i}{2}\hat{a}^{\dagger}_{\rightarrow,l,+}\hat{a}^{\dagger}_{\leftarrow,u,-}|0\rangle\alpha|m_+\rangle \\ &+\frac{i}{2}\hat{a}^{\dagger}_{\rightarrow,u,+}\hat{a}^{\dagger}_{\leftarrow,l,-}|0\rangle\beta|m_-\rangle \\ &+\frac{1}{\sqrt{2}}|scattered\rangle \end{aligned} \tag{5}$$

where $|scattered\rangle$ is the normalized state vector corresponding to the situation that the atom absorbed one probe photon and emitted one scattered photon by decaying to the ground state afterward. If the probing photons were not absorbed there are three possible outcomes: $D_{\rightarrow,u}$ and $D_{\leftarrow,u}$ fire; $D_{\rightarrow,l}$ and $D_{\leftarrow,u}$ fire; $D_{\rightarrow,u}$ and $D_{\leftarrow,l}$ fire. In the case that the photons are detected by the two upper detectors, the presence of the atom is not discovered, and the state of the atom remains unchanged so we can repeat the experiment. In contrast, if only one $+$ or $-$ polarized photon is used, as shown in [7] the state of the atom is changed even if its existence is not successfully detected. In this sense the two photon scheme is closer to the original EV proposal. Here we see that the two photon scheme is not identical to doing the experiment twice with the single photon method, because the atom interacts with the larger Hilbert space spanned by the two probe photons and the whole system is measured only once. When one of the lower detectors fires, we have discovered the atom successfully without it absorbing the photon, but it is not a nondistortion interrogation because the initial superposition of the atom is destroyed and the atom is left in either $|m_+\rangle$ or $|m_-\rangle$, with probabilities $|\alpha|^2/4$ and $|\beta|^2/4$ respectively. What happened is that the wave functions of the atom and photons got entangled when the photons were propagating through the interferometer and partially absorbed by the atom, so that a measurement of the photons projects the atom to a state which is different from its initial superposition.

Let us go one step further and make use of an EPR entangled photon pair as our probe:

$$|\psi_{photon}\rangle = \frac{1}{\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,l,+}\hat{a}^\dagger_{\leftarrow,l,-} + \hat{a}^\dagger_{\rightarrow,l,-}\hat{a}^\dagger_{\leftarrow,l,+})|0\rangle \quad (6)$$

By the same considerations we can show that the final state of the system is

$$\begin{aligned}
&\frac{1}{2\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,u,+}\hat{a}^\dagger_{\leftarrow,u,-} + \hat{a}^\dagger_{\rightarrow,u,-}\hat{a}^\dagger_{\leftarrow,u,+})|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&+\frac{i}{2\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,u,-}\hat{a}^\dagger_{\leftarrow,l,+}|0\rangle\alpha|m_+\rangle + \hat{a}^\dagger_{\rightarrow,u,+}\hat{a}^\dagger_{\leftarrow,l,-}|0\rangle\beta|m_-\rangle) \\
&-\frac{i}{2\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,l,+}\hat{a}^\dagger_{\leftarrow,u,-}|0\rangle\alpha|m_+\rangle + \hat{a}^\dagger_{\rightarrow,l,-}\hat{a}^\dagger_{\leftarrow,u,+}|0\rangle\beta|m_-\rangle) \\
&+\frac{1}{\sqrt{2}}|scattered\rangle \qquad (7)
\end{aligned}$$

If we use x and y polarization

$$\begin{aligned}
\hat{a}^\dagger_x|0\rangle &= \frac{1}{\sqrt{2}}(\hat{a}^\dagger_- - \hat{a}^\dagger_+)|0\rangle \\
\hat{a}^\dagger_y|0\rangle &= \frac{i}{\sqrt{2}}(\hat{a}^\dagger_- + \hat{a}^\dagger_+)|0\rangle \qquad (8)
\end{aligned}$$

the final state can be rewritten as

$$\begin{aligned}
&-\frac{1}{2\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,u,x}\hat{a}^\dagger_{\leftarrow,u,x} + \hat{a}^\dagger_{\rightarrow,u,y}\hat{a}^\dagger_{\leftarrow,u,y})|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&-\frac{i}{4\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,u,x}\hat{a}^\dagger_{\leftarrow,l,x} + \hat{a}^\dagger_{\rightarrow,u,y}\hat{a}^\dagger_{\leftarrow,l,y})|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&+\frac{1}{4\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,u,x}\hat{a}^\dagger_{\leftarrow,l,y} - \hat{a}^\dagger_{\rightarrow,u,y}\hat{a}^\dagger_{\leftarrow,l,x})|0\rangle(\alpha|m_+\rangle - \beta|m_-\rangle) \\
&+\frac{i}{4\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,l,x}\hat{a}^\dagger_{\leftarrow,u,x} + \hat{a}^\dagger_{\rightarrow,l,y}\hat{a}^\dagger_{\leftarrow,u,y})|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&+\frac{1}{4\sqrt{2}}(\hat{a}^\dagger_{\rightarrow,l,x}\hat{a}^\dagger_{\leftarrow,u,y} - \hat{a}^\dagger_{\rightarrow,l,y}\hat{a}^\dagger_{\leftarrow,u,x})|0\rangle(\alpha|m_+\rangle - \beta|m_-\rangle) \\
&+\frac{1}{\sqrt{2}}|scattered\rangle \qquad (9)
\end{aligned}$$

Now we see that if the polarizations of the 4 detectors are chosen to be x, y instead of $+$ and $-$, there are 5 possible outcomes if no photon was absorbed: (a) the photons are detected by $D_{\rightarrow,u}$ and $D_{\leftarrow,u}$ in the same polarization (x or y); (b) the photons are detected by $D_{\rightarrow,u}$ and $D_{\leftarrow,l}$ in the same polarization; (c) the photons are detected by $D_{\rightarrow,u}$ and $D_{\leftarrow,l}$ in different polarizations; (d) the photons are detected by $D_{\rightarrow,l}$ and $D_{\leftarrow,u}$ in the same polarization; (e) the photons are detected by $D_{\rightarrow,l}$ and $D_{\leftarrow,u}$ in different polarizations. Among them, in case (b) and (d) the atom is left in its initial superposition and a successful NQI has been realized. The probability of a successful NQI is 1/8, twice higher than that of the single photon scheme as in [7]. In case (c) and (e), the existence of the atom is also detected, but there is a phase shift of π in the superposition of the atomic state. The probability for such an event is also 1/8. If the photons are received by the two upper detectors (with probability 1/4), they must have the same polarization and the initial superposition of the atom is unperturbed. In this case the presence of the atom is not discovered and the experiment can be repeated. Also, we note that $D_{\rightarrow,l}$ and $D_{\leftarrow,l}$ never fire together. This is a consequence of the polarization selective photon-atom interaction. When the photons passed through the atom their wave functions got entangled if no photon was absorbed by the atom. The interference between the upper and lower branches of the photon wave function in the interferometer is such that the two photons never both exit from the lower ports.

In the above observation, we see that the correlation in the probe system and the joint measurement of the states of the photons are keys to the nondistortion interrogation of the atom with an increased success probability. By using an EPR entangled photon pair, we effectively expanded the Hilbert space spanned by the probe system. The joint measurement of the states of the two photons with linearly polarized photon detectors allows us to map half of the object-discovering results to initial superposition preserving interrogations.

We should point out that in the single photon scheme as in [7], when the upper (polarization sensitive) detector fires, it is still possible to find out the existence of the atom if the polarization of the probing photon was changed. In that case the initial atomic superposition was changed too. This is possible because polarization of the photon provides an additional degree of freedom. If a right going x polarized photon is used as the probe, the process is

$$\begin{aligned}
&\hat{a}^\dagger_{\rightarrow,l,x}|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \longrightarrow \\
&-\frac{3}{4}\hat{a}^\dagger_{\rightarrow,u,x}|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&+\frac{1}{4}i\hat{a}^\dagger_{\rightarrow,u,y}|0\rangle(\alpha|m_+\rangle - \beta|m_-\rangle) \\
&+\frac{1}{4}i\hat{a}^\dagger_{\rightarrow,l,x}|0\rangle(\alpha|m_+\rangle + \beta|m_-\rangle) \\
&-\frac{1}{4}\hat{a}^\dagger_{\rightarrow,l,y}|0\rangle(\alpha|m_+\rangle - \beta|m_-\rangle) \\
&+\frac{1}{2}|scattered\rangle \qquad (10)
\end{aligned}$$

To discuss this in a more general framework, we can think of NQI as the discrimination between the absence and presence of quantum coupling (interaction Hamiltonian) between the object and probe system without destroying the probe particles. When the wave functions of the object and probe overlap in space, the coupling is present and the two parts which were initially independent (the probe and object) will be entangled. By carefully designed unitary operations and measurements on the probe system one tries to obtain information on the presence of the coupling without disturbing the internal state of the object. From this point of view, a good

NQI scheme is one which is most likely to keep the internal state of the object unchanged while simultaneously bring the probe system to a state orthogonal to that corresponding to no coupling in some carefully chosen basis. What our result suggests is that the probe system and the operations and measurements on it have to be very carefully designed for the purpose of NQI, due to the fragility of quantum superposition. Nevertheless, it can be shown that NQI can be done for an object in quantum superposition with efficiency approaching unity [8]. Whether a more general consideration can be formulated and the connection to quantum information is of further interest to us [9] [10].

In conclusion, we have provided a new scheme for nondistortion quantum interrogation by using a pair of EPR entangled photons. It enables us to monitor the presence of an object without destroying its state of superposition. Due to the expanded Hilbert space of the probe photons, it is shown that our scheme yields a higher probability for successful nondistortion interrogation of the atom than the single photon scheme. If the existence of the atom is not successfully detected, the experiment can be repeated since the atomic state is unperturbed. This method of nondistortion interrogation of quantum objects characterized by its superposition may find its application in future quantum information processing.

Work of Z.W.Z. and G.C.G. was funded by National Natural Science Foundation of China. Research of X.Z. and M.J.F. was supported in part by ARO grant DAAG55-98-1-0367.

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